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^{252}Cf — THE VERSATILE NEUTRON SOURCE

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INTRODUCTION

Californium-252 is probably the most versatile neutron source yet developed, when the great variety of possible forms and applications is considered.[1] Its outstanding features are the copious emission of neutrons from a physically small package, low heat generation, and a 2.64-year half-life. There is no technical limit to the strength of a ^{252}Cf neutron source; therefore, ^{252}Cf is capable of bridging the gap between the neutron output of existing α-n neutron sources and the neutron production of a small nuclear reactor.

This paper is a comprehensive review of the present state of development of applications of ^{252}Cf neutron sources.

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Applications in life sciences, education, chemical analysis, exploration for natural resources, industrial process control, neutron radiography, nondestructive inspection, neutron flux enhancement, nuclear reactor startup, and fission-product bombardment are described.

The element californium (atomic number 98) was synthesized in 1950 by Seaborg and co-workers by bombarding microgram quantities of ^{242}Cm with 35 Mev helium ions in the 60-inch cyclotron at Berkeley.[2] The isotope ^{252}Cf was initially produced in the first thermonuclear explosion at Eniwetok Island in 1952, and was later separated from the debris of the test.[3] In the next six years, about 30 micrograms of ^{252}Cf was produced in the Materials Test Reactor at Arco, Idaho. Subsequently, larger amounts were produced in the High Flux Isotope Reactor at Oak Ridge National Laboratory and in the production reactors of the Savannah River Plant of the United States Atomic Energy Commission; in the past two years, over 2 grams of ^{252}Cf was produced at these two sites.

The outstanding property of ^{252}Cf is the copious emission of neutrons, 2.3×10^{12} n/sec gram. Indeed, the emission is so great that normally neutron sources are considered as comprising milligram or microgram quantities of ^{252}Cf; hence, miniature, although extremely powerful, neutron sources are possible. The effective half-life of ^{252}Cf, 2.64 years, is governed by the alpha decay rate of the isotope. The nuclear and physical

properties of ^{252}Cf have been summarized by Prince[4] and the radiation properties by Stoddard.[5]

Although ^{252}Cf is properly thought of as a neutron source it in fact emits three principal forms of radiation in its decay process: neutrons, alpha particles, and gamma photons. As shown in Table 1, 96.9% of the californium atoms decay by alpha emission to form helium gas and the isotope ^{248}Cm. In a practical neutron source, the helium is contained within the capsule, and even at total decay, helium does not present a problem of pressure buildup.

The 3.1% of californium atoms that undergoes spontaneous fission provides neutrons with a spectrum of energies (Figure 1) similar to the fission spectrum of ^{235}U. The energy distribution of californium neutrons is compared with those of neutrons from other sources in Figure 2. Approximately six gamma photons are produced for each neutron released by spontaneous fission. The majority of these gammas have energies less than 2 Mev, as shown in Figure 3. The fission products and the alpha particles are contained within the sealed neutron source. Thus, in a working source, californium emits neutrons and gamma rays. If a pure neutron source is desired, the gamma rays can be attenuated by a suitable filter, but in most applications these gamma rays are of lesser importance than the gamma rays produced by interactions of the californium neutrons with the surroundings.

MANUFACTURE OF CALIFORNIUM-252

Adequate Supply

Californium-252 is produced by the extended irradiation of ^{239}Pu or heavier isotopes, such as ^{243}Am and ^{244}Cm, in reactor charges that operate at a neutron flux of about 10^{15} n/cm^2 sec. This high-flux requirement limits the production of ^{252}Cf to a few specially designed reactors, such as the High Flux Isotope Reactor at Oak Ridge National Laboratory,[6] or a high-flux charge in a Savannah River production reactor,[7,8] and eliminates the conventional power reactor as a potential supplier of ^{252}Cf. If future demands for ^{252}Cf are large, however, the power reactor industry may provide the transplutonium isotopes of americium and curium that will be needed as feed (targets) for ^{252}Cf production.[9]

After several months of cooling, the irradiated targets are dissolved, and the californium isotopes are separated by pressurized ion-exchange chromatography in heavily shielded, remotely operated chemical separation facilities.[10-13] The isotopic composition of the californium product depends on the conditions of irradiation, and the possible ranges of the several californium isotopes are shown in Table 2. Only traces of ^{253}Cf and ^{254}Cf are present because of their much lower initial concentration and much higher rates of decay.[14]

The chemical purity of the separated californium is summarized in Table 3. Purity is important in the fabrication of

the neutron source, because the processes of electrodeposition or precipitation in source fabrication require high-purity californium to achieve the desired uniformity and control.

Several vendors have announced an interest in encapsulating and selling ^{252}Cf sources.[15]

The price of ^{252}Cf will depend on the demand for this isotope. Some indications of possible price ranges previously given by the USAEC[16] are shown in Table 4.

Design and Fabrication of Neutron Sources

When the total quantity of the neutron emitter is at most several milligrams, entirely new concepts of neutron source design and fabrication are possible. Because ^{252}Cf is a spontaneous neutron emitter and does not rely on any secondary reactions to generate the neutrons, the techniques for preparation of the fabricated neutron source can be tailored to fit a wide variety of applications.

Small californium neutron sources, such as those used for radiotherapy (1 to 20 microgram or 2×10^6 to 4×10^7 n/sec), are prepared by electrodeposition.[17] In this process, $Cf(OH)_3$ is deposited from an aqueous solution onto a suitable substrate, and then oxidized in place to form an adherent deposit of Cf_2O_3. Experience has shown that high purity californium is the key to a successful electrodeposition technique. Doubly encapsulated linear sources 0.95 mm in diameter, and either 1.6 or 3.1 cm

long are prepared by this technique for cancer therapy research. The capsules are platinum-10% iridium alloy, with inert arc-welded closures. A typical welded closure is shown in Figure 4.

In the future, the electrodeposition technique for these relatively short linear sources should be applicable to longer sources, perhaps even with specified gradients of neutron yield along the length of the source. If desired, californium could be electro-deposited on planar, cylindrical, or irregular surfaces, according to the needs of the user. There is a growing demand for annular and linear sources for industrial and research applications.[18]

Large californium sources (0.1 to 10.0 milligrams) have been prepared by precipitating $Cf_2(C_2O_4)_3$ inside a specially designed platinum-rhodium filter capsule (Figure 5) and calcining to Cf_2O_3. The filter capsule is then encapsulated in stainless steel or Zircaloy.[19,20] The finished capsule is shown in Figure 6. In an alternative process,[21] the ^{252}Cf is deposited on an ion exchange resin in an aluminum filter capsule, fired to decompose the resin, cold compacted to consolidate the ashed resin, and then encapsulated in a secondary corrosion-resistant capsule (Figure 7). Both of these techniques produce essentially a "point" neutron source, in which the californium occupies a volume of less than 1 cubic centimeter.

The materials used in the primary and secondary capsules influence the thermal neutron flux developed in a water moderator by a given amount of ^{252}Cf.[22] In certain analytical applications, the presence of metals such as iron, chromium, nickel, and manganese in the capsule create an undesirable background radiation in the detection system. In these cases, a quartz capsule (Figure 8) may be desirable.[23] Alternatively; Zircaloy-2 maybe used as the capsule material.

A new process that will simplify the source fabrication process and reduce the expense of encapsulation is being developed.[24] In this process, ^{252}Cf is produced either as a cermet or alloy with palladium in the form of compacted pellets, rods, or wires. The wire shown in Figure 9 contained about 1 wt % ^{252}Cf. The cermet is prepared by mixing Cf_2O_3 with palladium powder. Cf_2O_3 is thermally stable, has the refractory characteristics of the rare earth oxides, and is expected to melt at about 2300°C. The alloy can be formed by reducing Cf_2O_3 to metal and alloying the metal with palladium.

Palladium has many advantages as a matrix metal:

- Melting point of 1552°C
- Oxidation and corrosion resistant
- Not strongly activated by neutrons
- Soluble in HNO_3, which simplifies the recovery of ^{252}Cf from spent sources
- Alloys extensively with californium
- Easily formed into wire and sheet

The cermet or alloy forms should simplify the encapsulation of neutron sources, because the wet chemistry processes of precipitation or electrodeposition will be avoided. If a clad wire form can be developed, the problems of alpha contamination may be avoided, and an encapsulator might only need to clip a section of californium-containing wire to a given length, corresponding to the neutron yield desired, and encapsulate the wire segment in a suitable secondary container system.

Fabrication technology and the design of californium neutron sources is only beginning. The chemistry of californium is similar to that of the lanthanides, and one might consider a variety of compounds, designed to be used as ceramic bodies or coatings containing small amounts of ^{252}Cf. As the metallurgy of californium develops, and the fabrication of alloys and cermets of californium is better understood, many attractive possibilities in the design and manufacture of neutron sources will surely be explored.

Calibration is the final step in the preparation of each neutron source. An electronic method was developed that requires about 10 minutes to assay ^{252}Cf sources between 1 microgram and 50 milligrams.[25] The assay is made by placing the ^{252}Cf source in the center of a polyethylene moderator and measuring the resulting thermalized neutrons with fission counters in the moderator. All measurements are referenced to a ^{252}Cf source calibrated with a manganese sulfate bath by the National Bureau

of Standards. Measurements of ^{252}Cf content agree with manganese sulfate bath determinations to within ±0.6%.

Safety and Handling

Shielding the ^{252}Cf neutron source to protect the user from neutron and gamma radiation is the principal requirement in safely handling the isotope.[26] Other safety considerations, such as self-heating, pressure buildup, and toxicity, are relatively less important in a well-designed neutron source. Criticality is not a problem.

Shielding for ^{252}Cf requires an evaluation of both neutron and gamma shielding.[27,28] For sources larger than 0.1 milligram, a multicomponent shield is most efficient and economical. Most shields have three regions: a) an inner region next to the source comprising a dense material to attenuate the gamma rays from the californium source; b) a middle region containing a hydrogenous material to thermalize and capture the neutrons from the source; and c) an outer region, which again is a dense material, usually steel, to attenuate the gamma rays produced by the capture of neutrons in the hydrogenous middle region. The water-extended polyester resins have recently been shown to be convenient neutron shields.[29,30] Shields have been designed and built for ^{252}Cf sources as small as 1 microgram and as large as 1 gram. Sources up to 0.1 milligram (2×10^8 n/sec) can be handled conveniently

in paraffin-filled drums commonly used to ship and store polonium-beryllium and plutonium-beryllium sources, as shown in Table 5.

Compared to the problems of shielding, other safety and handling aspects are more easily managed. Criticality is not a problem with ^{252}Cf neutron sources.[31] Fissioning of ^{252}Cf is spontaneous, and the output of neutrons is directly proportional to the mass of ^{252}Cf present. Californium-251 is the only californium isotope that has a small critical mass (about 10 grams in a water-reflected metal-water mixture), but in reactor-produced californium, ^{251}Cf is present in such small amounts that it is practically impossible to accumulate enough to develop a criticality problem. For example, about 200 grams of ^{252}Cf would be needed to accumulate a critical mass of the accompanying ^{251}Cf.

Self-heating does occur because ^{252}Cf releases 38.5 watts per gram; however, in neutron sources of practical sizes (milligrams or less), heat load per unit of surface area is usually so small that the temperature rise is easily tolerated. For example, the largest industrial source (10 milligrams) of the design produced at Savannah River releases 0.38 watt and reaches an equilibrium temperature of 59°C in still air. Again, because a practical source contains relatively little californium, pressure buildup due to decay helium is not a serious problem. At 60°C, and after 10 years decay, the pressure inside a 10-milligram source

would reach only 160 psi. The burst pressure for the capsule is ∿14,600 psi.

Californium-252 is a highly toxic, relatively short-lived alpha emitter. The whole body burden that produces the maximum permissible dose rate to bone is estimated to be only 0.01 microcurie (1.9×10^{-5} microgram).[32] In practical applications release of ^{252}Cf is avoided by double encapsulation under strict quality control and inspection specifications.

Neutron Reactions of Californium-252

Neutron reactions may be classified in seven groups, each of which has already found some practical applications. The seven groups of reactions and a few specific examples are cited below. Some of these (2, 4, and 6) involve thermal neutrons; thus it is necessary to thermalize the ^{252}Cf fission neutrons for these and for many other applications. Nichols[33] presented data to estimate the neutron fluxes and shielding requirements for simple irradiation devices that use a ^{252}Cf neutron source.

1. *Fast Neutron, Decay Gamma*

   The fast neutron reaction with fluorine $^{18}F(n,\alpha)^{16}N$, followed by measurement of the 6.1 and 7.1 Mev gamma rays that accompany the decay of ^{16}N, which has a 7.2 second half-life, may be used for the nondestructive analysis of fluorine in the presence of oxygen in a wide variety of organic and inorganic matrices.

2. *Thermal Neutron, Decay Gamma*

Conventional thermal neutron activation analysis is also feasible with ^{252}Cf. In this technique, the neutrons from ^{252}Cf are first thermalized, usually by H_2O, the sample is then irradiated with thermal neutrons to produce temporarily radioactive species, and the subsequent decay gamma rays are analyzed and counted to provide a quantitative analysis of the desired elements. The measurement is similar to activation analysis using a nuclear reactor as the neutron source. In a nuclear reactor, the thermal neutron flux is typically 10^{13} n/(cm^2 sec), while even with a 100-milligram ^{252}Cf neutron source the thermal flux from a ^{252}Cf source would be about 10^9 n/cm^2 sec). With ^{252}Cf, larger samples and more sensitive counting techniques would be required even to approach the limits of detection possible with a nuclear reactor. To be competitive, the californium neutron source must then rely on other advantages, such as ease of operation, portability, and uniformity of the neutron flux.

3. *Inelastic Scattering*

Gamma rays (4.4 Mev) from inelastic neutron scattering from carbon may be useful in estimating the carbon content in "sinter mix," a mixture of coke, iron, and flux prepared as feed for blast furnaces in the steelmaking process.

4. *Thermal Neutron Capture Gamma*

Capture gamma techniques provide a powerful tool for on-

stream measurements of materials in bulk solids and slurries. This technique is based on the release of gamma rays of discrete energies from a given element at the instant the nucleus of that element captures a thermal neutron. The characteristic capture gamma spectra of materials provide "signatures" for many elements of commercial interest, and the instantaneous response allows quantitative measurements to be made of the amount of a given element present regardless of the flow rate past the sensor. One of the important advantages of the capture gamma technique is the ability to analyze large samples, sometimes as much as several hundred kilograms at one time.

Rasmussen *et al.*[34] have catalogued the thermal neutron capture gamma ray spectra of most of the elements, and also have listed them in terms of increasing gamma-ray energy.[35] Senftle *et al.*[36,37] have tabulated the analytical sensitivities and energies of the thermal neutron capture gamma rays to provide a guide for the practical application of the technique, particularly for the analysis of minerals.

5. *Neutron Thermalization*

Thermalization of fission-energy neutrons by hydrogen and detection of the thermal neutrons is the basis for several techniques for moisture measurement in soils and explosives.

6. *Thermal Neutron Attenuation*

Thermal neutron radiography with reactor neutron sources has

become an accepted method for nondestructive inspection. Neutron radiography is invaluable for the detection of hydrogenous materials behind dense materials, and for other special inspections that cannot be performed with gamma or X-rays. In this technique, the attenuation of thermal neutrons by an object is recorded by a neutron-sensing system behind the object. Californium-252 can be used as the source of neutrons, and the results can be recorded either by a converter-film or scintillator-film combination,[38] or possibly by a neutron-detecting instrument set up to make a "go, no-go" inspection.

The possibilities of slow-neutron transmission analysis for analysis of hydrogen in hydrocarbons have been recognized since 1965,[39] and its adaptability to on-stream process control is well known.

7. *Fast Neutron Attenuation*

The attenuation of fast neutrons has been used to measure the water content of soil samples[40] and marine sediments in unextruded ocean cores.[41] Fast neutron radiography, which would record the attenuation of fast neutrons by the object, would be an ideal application for a "point" neutron source, such as ^{252}Cf. Although no system for imaging fast neutrons is now commercially available, an etched plastic detector system utilizing the neutron-proton elastic scattering principle may provide a useful and inexpensive method.[42]

The versatility of ^{252}Cf can best be illustrated by the variety of applications that has already been found, or which suggest themselves as possibilities for the future.[43] Let us now consider some of the uses to which ^{252}Cf has been, or might be, applied.

CALIFORNIUM-252 APPLICATIONS

Life Sciences

In the field of medicine, ^{252}Cf is receiving much attention as a radiation source for possible use in cancer therapy. First proposed in 1965,[44] the availability of long, thin, needle-like neutron sources for both interstitial or intracavitary application of neutrons (and gamma rays) to cancerous tissue has captured the interest of cancer researchers.[45] Neutron dose calculations[46-48] have been made to estimate the radiation dose transferred to tissue by californium sources. Because of the high linear energy transfer (LET) of fast neutrons, this type of radiation may be more effective than gamma or X-rays in destroying cancer cells in anoxic or oxygen-deficient areas, such as exist in the center of large tumors. Recent studies at the M. D. Anderson Hospital and Tumor Institute with mouse jejunal crypt cells indicated that ^{252}Cf may be five times more effective than radium in killing mammalian cells.[49] Under an experimental program formulated by the USAEC's Division of Biology and Medicine, eleven hospitals and research institutions in the United States and the United Kingdom are now

evaluating ^{252}Cf for eventual use in cancer therapy. Experiments in dosimetry[50] and preliminary human radiobiological tests are in progress.[51]

In vivo activation analysis of all or part of the human body has been considered using radioisotopes such as $^{238}PuBe$ or ^{252}Cf as the neutron source.[52] The measurement of total body calcium is important to determine the progress of certain bone diseases. In Japan, the accumulation of cadmium in the kidneys is related to the so-called *Itai-itai* disease — a result of chronic cadmium poisoning. An almost uniform neutron irradiation to study either calcium or cadmium levels might be produced by exposing the body to one or more ^{252}Cf sources, moving rapidly in a helical path around the patient, or perhaps only around the trunk or an extremity, such as an arm or leg. Total calcium would be determined by irradiation to form ^{49}Ca by the $^{48}Ca(n,\gamma)^{49}Ca$ reaction, followed by measurement of the decay of ^{49}Ca, which is accompanied by the emission of 3.09 and 4.05 Mev gamma rays. For the measurement of cadmium, the prompt capture gamma reaction that produces a 5.82 Mev gamma ray may be useful.

A similar device, operating on a smaller scale, has been proposed to measure the sodium content of skin tissue,[53] as an indication of the incidence of cystic fibrosis, which causes abnormally high sodium levels in the perspiration of affected

individuals. This device would irradiate a small patch of skin to produce ^{24}Na by the $^{23}Na(n,\gamma)^{24}Na$ reaction, followed by measurement of the 2.75 Mev decay gamma ray of ^{24}Na as an indication of the sodium level.

In medical research, the possibility of neutron radiography with ^{252}Cf has been considered,[54] but the long exposure times and lack of resolution will probably limit the usefulness of this application to work with pathological specimens and animal studies.

However, in biological and botanical research exploring the effects of controlled exposure to neutrons, a ^{252}Cf irradiator should have many useful features. By proper combinations of moderating materials, an annular zone of almost uniform neutron and gamma flux could be constructed in which animals, such as mice, fish, or insects, could be given controlled doses of radiation for research purposes.

Similarly, neutron irradiation of seeds for plant mutation studies could be conducted under closely controlled conditions in any country in the world, at any location, without the complications involved in the construction and operation of a nuclear research reactor.

Education and Research

Californium-252 will provide neutron irradiators for training of students. Small californium sources of 0.1 milligram (2×10^8 n/sec) are suitable for classroom demonstrations of neutron effects,

because the source and its shield can be moved conveniently from laboratory to laboratory, and from experiment to experiment as desired.[55,56] Since each source is calibrated at the time of encapsulation, the neutron output may be calculated precisely at all times.

For research work requiring higher neutron fluxes, larger ^{252}Cf sources producing calibrated yields of neutrons from 2×10^{9} to 2×10^{11} n/sec are possible. The maintenance-free quality of the source and the known output of neutrons, night and day, month after month, would allow greater utilization of the source than is possible with either a reactor or accelerator. Production of radioisotopes by neutron capture can be carried out when the irradiator is not being used for other studies.

Analytical Chemistry

The strength of the neutron source required for laboratory activation analysis represents a balance between the size of the sample, the concentration of the element to be measured, and the sensitivity of the measuring system. One milligram of ^{252}Cf provides 2×10^{9} n/sec, from which a useful thermal neutron flux of 10^{7} n/cm^{2}/sec can be obtained. This flux level is adequate for the analysis of mineral specimens at concentrations of economic interest. Table 6[57] lists the calculated detectable concentrations of 22 elements in mineral samples assuming a 5-kilogram sample of the appropriate mineral, a 1-milligram ^{252}Cf neutron source, irradiation and counting times of 2 minutes, and

an 80-cm^3 Ge(Li) detector.

Calculated sensitivities and detection limits for twelve commercially important metals were given by Ricci and Handley[58] for a 10-milligram ^{252}Cf source and two 12.7-cm x 12.7-cm NaI(Tl) detectors.

Preliminary experiments[59] indicate that sensitivities of 1 ppm for about 46 of the more easily activated elements should be achieved with a 5-milligram ^{252}Cf source. A neutron irradiator containing a total of 8 milligrams of ^{252}Cf in an array of 8 sources was studied by the National Bureau of Standards, who reported that the reproducibility of the system was excellent.[60] A series of ten analyses showed a standard deviation of less than 0.1 percent on a vanadium compound (NBS Standard Reference Material 1052a). Fast neutron activation analysis was used to determine fluorine in several materials by measuring the short half-life isotope ^{16}N produced by the $^{19}F(n,\alpha)^{16}N$ reaction. On the basis of a 30-second irradiation and 60-second count, a standard deviation of about 0.1% for the fluorine determination was obtained.

Exploration for Natural Resources

Its small size and high neutron yield make ^{252}Cf attractive for terrestrial and undersea exploration for natural resources.

The United States Geological Survey (USGS) has evaluated ^{252}Cf neutron sources for *in situ* neutron activation of many commercially important minerals. Beginning with a study of the distribution of neutrons from a ^{252}Cf source in soil,[61] the USGS has applied ^{252}Cf to the exploration of silver, gold, manganese, titanium, nickel, and uranium.

The experiments with silver[62] were made to compare neutron accelerators with ^{252}Cf for *in situ* activation of silver. Tests were made with simulated ore deposits, a 90-microgram ^{252}Cf neutron source, and a NaI(Tl) detector coupled to a 100-channel multichannel analyzer. The neutron source was mounted in a 55-gallon drum of water on the tailgate of one vehicle, and the detector system was in a second vehicle which was positioned over the previously irradiated spot to detect the decay gamma rays from the activated silver. The test revealed better sensitivity with the ^{252}Cf source than with the accelerator source operated with comparable techniques. It was estimated that silver could be detected at <1 oz per ton with the ^{252}Cf source.

The objective of the USGS study on manganese and gold was to obtain spectral signatures that could be clearly identified in the complicated spectra from seawater.[63] Prompt capture gamma spectra were obtained with a 67-microgram ^{252}Cf neutron source and a 30-cm^3 Ge(Li) detector in a laboratory setup that simulated either a freshwater or seawater environment. Although chlorine

presented some interference, there were several peaks of manganese and gold for which there was no significant interference.

The detection and analysis of a titanium ore was studied with a 120-microgram ^{252}Cf neutron source and a 30-cm^3 Ge(Li) detector.[64] On the basis of 100-minute irradiations, the percent TiO_2 in the ore indicated by the capture gamma ray technique compared favorably to a chemical analysis (14.4% against 14.6%).

Nickel exploration and analysis by neutron capture gamma rays have been investigated.[65] A 115-microgram ^{252}Cf source and a 30-cm^3 Ge(Li) detector coupled to a 400-channel pulse-height analyzer were used. Analyses down to 0.1 percent nickel generally compare favorably to chemical analyses. Tests in an artifically prepared surface deposit and in a test borehole indicated that a low grade (~1% nickel) ore deposit was easily detected.

An activation analysis technique for uranium ore, suitable for field application, was tested by the USGS.[66] The method measures the 74.7-kev gamma ray obtained from ^{239}U by irradiating about 25 grams of ore with epithermal neutrons from a 100-microgram ^{252}Cf source. The specimens were activated for 20 minutes, and counted for 10 minutes with two NaI(Tl) detectors. An accuracy of 10% was obtained for uranium in low-vanadium and low-chromium ores.

A system for seabed mineral exploration using a 200-microgram ^{252}Cf neutron source and a Ge(Li) detector has been designed for

decay gamma ray analysis by Battelle-Northwest Laboratories.[67] The probe will analyze *in situ* for minerals on the ocean floor at a water depth of a few hundred feet. Analyses could be obtained at 5-minute intervals. The decay gamma procedure also was demonstrated in a series of underwater tests conducted jointly by the University of Georgia, Oceanonics, Inc., and the Westinghouse Ocean Research Laboratory.[68] Elemental analysis of minerals in ore-grade concentrations was successfully demonstrated using an undersea submersible for deep water, a sled for intermediate depths, and scuba divers for shallow water.

Borehole logging for minerals is a rapid and efficient method for exploring mineral deposits. Initial experiments with ^{252}Cf at the Savannah River Plant[69] have been followed by developments at USGS and Kerr-McGee Corporation.

The USGS and Princeton Gamma-Tech., Inc. have built a prototype borehole sonde containing a ^{252}Cf neutron source and a Ge(Li) detector which is cooled by a melting cryogen.[70,71] The detector is stabilized at -188°C for as much as 10 hours by a sealed cryostatic reservoir containing melting propane.

Kerr-McGee Corporation has developed a mobile system consisting of 1 milligram of ^{252}Cf in a shielded trailer (Figure 10) attached to a logging truck equipped with data-processing equipment.[72] The system will be used to determine the extent and uranium content of deep-lying ore deposits by measuring the delayed

neutrons produced by interaction of the californium neutrons with uranium in the ore deposit.[73]

Well logging for oil and gas involves the identification of potential oil-producing horizons in the earth formations surrounding a borehole. Texaco Inc. has evaluated ^{252}Cf neutron sources in five logging applications.[74] A dual-spaced neutron log for porosity was developed with a 700-microgram ^{252}Cf neutron source. Tests indicated that this log is: a) almost insensitive to the presence of casing in the borehole; b) almost insensitive to variations in borehole salinity; and c) only slightly affected by the position of the logging instrument in the borehole. However, the formation matrix must be known. Other techniques for which smaller neutron sources may be used include continuous activation logging, capture-gamma logging, neutron-gamma logging for gas, and chlorine logging.

Industrial Process Control

Many modern industrial processes could benefit from on-line elemental analysis of the process stream. Neutron techniques, such as conventional decay gamma analysis and prompt capture gamma analysis, require no sample preparation, are nondestructive, and can provide results in time to be used as a basis for process control. The relatively high penetrating power of the incident fast neutrons and the emitted gamma rays allows measurements to be made in flowing streams and reduces errors due to matrix hetero-

geneity and particle size. Californium-252 is a suitable neutron source for many of these techniques and in some cases is the preferred source, either because of its characteristic neutron spectrum or because of the need for a constant, high-intensity source with small physical dimensions.

Conventional decay gamma activation techniques with californium sources of 10^9 n/sec or larger require that a portion of the stream be exposed to neutrons in an irradiator, and the decay of the activated species be analyzed as the stream passes through a separate gamma detector.

An example of this technique is the on-stream vanadium analyzer built by the Gulf Research & Development Company,[75] Figure 11. The analyzer uses a 500-microgram ^{252}Cf source and is designed for continuous, accurate, and completely instrumental determination of vanadium in hydrocarbon streams. Vanadium from 0.1 ppm to several hundred ppm can be analyzed routinely with a standard deviation of ±0.02 ppm at the 1 ppm level.

A broad investigation of process control based on activation analysis with ^{252}Cf was made by the Columbia Scientific Industries.[76-79] A summary of the preferred reactions and observed yields are given in Table 7, and a sketch of their slurry loop for on-stream analysis is given in Figure 12. The loop may also be adjusted to recirculate samples through the counter without simultaneous irradiation. Potentially one of the most important applications of ^{252}Cf is the determination of calcium in cement

raw mix using the reaction $^{48}Ca(n,\gamma)^{49}Ca$ (decay γ, 3.1 Mev; half-life, 8.8 minutes). For other mineral applications, experimental determinations in a specific system using a 400-microgram ^{252}Cf source and a 6-inch x 6-inch NaI well crystal indicated detection limits (one standard deviation) of 25 ppm cobalt, 30 ppm Ag_2O (1 oz per ton), ~0.1% copper, and 400 ppm gold. Lower detection limits are possible with a larger ^{252}Cf neutron source and more sensitive counting systems.

Republic Steel Corporation developed an activation technique for measuring the manganese content of steel samples, cast as cylinders, 2 inches in diameter and 1.5 inches long.[80] It was concluded that a 1-milligram ^{252}Cf source could be used for activation analysis of manganese in steels and that matrix effect errors could be minimized by a suitable choice of sample irradiation position, which optimized the flux spectrum. In samples of unknown alloy content, manganese was determined to an accuracy of ±3% of the concentration. For low alloy bar stock and basic oxygen furnace steels, a 2-minute activation analysis yielded an accuracy of ±0.02% manganese.

For industrial process control, prompt capture gamma ray reactions have even greater potential than conventional activation reactions.[81] First, prompt analysis can accomodate relatively large samples (600 lb in the determination of sulfur in coal); second, analysis is immediate ; and third, the prompt gamma rays are usually high-energy emissions so that interfer-

ence from photopeaks (E <3 Mev) can be eliminated. In general, the equipment and procedures must be specially developed for each application, but the method appears to be particularly suitable for processing iron, copper, and nickel ore.[82]

The on-stream measurement of sulfur in coal has been extensively tested by the Bureau of Mines, U. S. Department of the Interior.[83,84] The sulfur meter contains an 80-microgram ^{252}Cf neutron source, and measures the sulfur content of coal flowing at a rate of 10 to 50 tons per hour (Figure 13). The measurement of the 5.4-Mev prompt gamma sulfur peak has a precision of ±0.02 wt percent sulfur, and readings are obtained every 4 minutes. A commercial version of the sulfur meter has been developed by American Science and Engineering, Inc.[85] As an extension of the work on the sulfur meter, the Bureau of Mines plans to use prompt gamma ray techniques to develop an ash meter and eventually a Btu meter to improve production efficiency in electrical power generation.[86]

A process control problem peculiar to the nuclear industry is assay of fissionable materials. Neutron interrogation techniques are useful, and ^{252}Cf is an outstanding neutron source for assay purposes.[87] Los Alamos Scientific Laboratory has investigated moderators for ^{252}Cf, designed to tailor the neutron spectrum for particular purposes.[88] A fuel rod assay system was designed to measure the total ^{235}U content of six 10-ft fuel rods in less than one minute with a counting statistical accuracy of better than 1%. In this device (Figure 14), the moderated neu-

trons from a 200-microgram ^{252}Cf neutron source interrogate the fuel material, and prompt neutrons from the induced-fission reactions are counted with energy-biased fast neutron detectors.

Another assay system for fissionable materials is available commercially from Gulf Energy and Environmental Systems, Inc.[89] This system contains a 25-microgram ^{252}Cf neutron source to produce a collimated beam of neutrons that interrogate the sample. Four plastic scintillators with photo-multipliers measure both the fast neutrons and the gamma rays produced in the sample by the source beam. The signal-to-noise ratio is reduced by requiring coincident signals in three of the four detectors as an indication of a fission event in the sample (Figure 15). Tests for ^{239}Pu analysis made at the AEC's Rocky Flats plant indicated that the active interrogation technique produced good results, particularly in the assay of plutonium-containing slag.[90]

Neutron Radiography for Nondestructive Inspection

The technique of thermal neutron radiography is rapidly becoming one of the standard methods for nondestructive testing in the aerospace, ordnance, and nuclear power industries. Neutron radiography complements X-radiography because neutrons are able to reveal the presence of hydrogenous materials within high-Z materials, are able to contrast isotopes of the same element (such as ^{235}U and ^{238}U), and, by means of transfer screens, can radiograph gamma-emitting objects such as irradiated fuel elements.

Most industrial neutron radiographs are made with neutrons from nuclear reactors. Small accelerators and radioisotopes are also used as neutron sources. A comprehensive review of the role of isotopes in neutron radiography that was made by the Argonne National Laboratory includes ^{252}Cf as one of the potentially useful neutron sources.[91] A summary of the work with ^{252}Cf at Argonne National Laboratory concludes that a sufficiently large ^{252}Cf neutron source could equal the image quality of a neutron radiograph made with a nuclear reactor. For high-quality radiographs, the exposure required is about 100 mg-hr; for example with a 10-mg ^{252}Cf source, a 10-hr exposure would be required. The high-quality ^{252}Cf neutron radiographs can be made by optimizing the radiographic system.[92]

Neutron radiography with ~1 milligram of ^{252}Cf has been extensively investigated at General Dynamics Convair Aerospace Division.[93] To determine the suitability of using ^{252}Cf for the radiographic inspection of a variety of aerospace materials and components, a simple, water-moderated facility shown in Figure 16 was constructed. Conventional direct-exposure techniques using X-ray film with gadolinium metal conversion screens in spring-loaded cassettes were used to obtain 5-inch by 7-inch neutron radiographs of several items. Defective pyrotechnic devices, rubber O-rings in sealed metallic valves, boron-fiber laminates, water droplets and sealants in honeycomb structure, and adhesive-bonded metallic lap-shear specimens were inspected with varying

degrees of success using a 5-inch-square beam of thermal neutrons. It was concluded that ^{252}Cf is suitable for the design and fabrication of an inexpensive, cheaply-operated facility for exploratory nondestructive test applications of many products with thermal neutron radiography.

Battelle-Northwest[94] also developed the small, portable neutron camera shown in cross section in Figure 17. This device contained about 270 micrograms of ^{252}Cf, and weighed only 350 pounds.

The development of neutron radiography with ^{252}Cf is continuing, and tests are now being made with 10-milligram ^{252}Cf sources, both at General Dynamics and the Picatinny Arsenal, Department of the Army. At Picatinny Arsenal, the ^{252}Cf system has already been used to examine a number of explosive boosters that could not be inspected by X-ray radiography.[95]

Slow neutron transmission analysis with ^{252}Cf neutron sources can be used for nondestructive testing for the presence or absence of hydrogenous materials. For example, it has been demonstrated with a 10-curie ^{239}Pu-Be neutron source that the presence or absence of a petroleum-base grease in sealed automotive clutch ball bearing assemblies[96] can be detected with properly designed equipment under production line conditions in about one second. With a ^{252}Cf source of about 100 micrograms, it is estimated that not just the grease/no-grease measurement could be made, but more importantly from a quality control outlook, changes in grease

loading of <10% of that in a fully loaded bearing could be detected.[39] Similar techniques might, for example, provide a "Yes-No" answer regarding the presence or absence of explosives or propellants in ordnance devices, or the location of gaskets and seals in manufactured equipment, or organic residues in metallic tubing.

Flux Enhancement with ^{252}Cf Neutron Sources

Subcritical multiplication of ^{252}Cf neutrons has been reported to increase the effective size of the neutron source by 6- to 20-fold,[97,98] and experimental work is now proposed both at Battelle-Northwest and the University of Texas[99] to investigate the the practicality of this approach. If satisfactory systems can be developed, the subcritical neutron multiplier would have the dual advantages of reducing both the initial investment and the annual decay cost of a larger ^{252}Cf source.

Reactor Startup Sources

During startup, nuclear reactors commonly use an auxiliary source of neutrons to provide initial readings on the neutron flux monitors. Isotopic neutron sources are employed as the primary startup source, and ^{252}Cf has several advantages in this application. The principal advantages are the low heat generation and small size of ^{252}Cf neutron sources, which greatly simplify the design and safety considerations for the startup source. In addition, there is no practical limit on the neutron flux provided

by ^{252}Cf, and the 2.6-year half-life allows some unscheduled delay in the startup date. In the AEC's production reactors at Savannah River, antimony-beryllium startup sources are being replaced by ^{252}Cf, and the Gulf General Atomic Company has already purchased two ^{252}Cf startup sources for the 841-megawatt (thermal) High Temperature Gas Reactor now being installed at the Fort St. Vrain Nuclear Generating Station.

Energetic Fission Products from ^{252}Cf

The last category of applications for ^{252}Cf uses the energetic fission products that result from the spontaneous fissioning of ^{252}Cf atoms. For example, a thin, unprotected layer of ^{252}Cf may serve as a continuous source of energetic fission products, which escape from the californium layer, and impinge on surfaces placed near the source. These energetic fission products cause local structural damage in the bombarded surface, and when the surface is chemically etched, the fission fragment tracks appear as small holes, or pores, in the surface.

A patent[100] describes thin porous films formed by the bombardment *in vacuo* of polycarbonate-poly(dimethylsiloxane) copolymers with fission products from ^{252}Cf, followed by extraction of the decomposed portions of the film with NaOH solution. The resulting film is 6-micron thick and contains cavities and openings about 20,000 Å in diameter. These films are useful as filters, as molecular sieves, and, after the pores are filled with iron-

containing particles, as image surfaces for television cameras.

This bombardment-and-etch technique might also be used as a surface-roughening technique to improve the adhesion of deposited films, or to provide other microscopic surface effects.

Fission product bombardment has also been suggested[101] as a technique for creating secret markings for identification of rare documents and objects of art, and as an internal monitor to detect tampering of neutron flux monitors.[102]

These uses require that the surface containing ^{252}Cf be exposed to the environment; therefore, the problems of toxicity that might possibly be encountered must also be considered.

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TABLE 1

NUCLEAR PROPERTIES OF ^{252}Cf

Mode of decay	
Alpha emission	96.9%
Spontaneous fission	3.1%
Half-life	
Alpha decay	2.731 ±0.007 years
Spontaneous fission	85.5 ±0.5 years
Effective (α and SF)	2.646 ±0.004 years
Neutron emission rate	2.31×10^{12} n/(sec-g)
Neutrons emitted per spontaneous fission	3.75
Average neutron energy	2.348 Mev
Average alpha particle energy	6.117 Mev
Gamma emission rate (exclusive of internal conversion X-rays)	1.3×10^{13} photons/(sec-g)
Dose rate at one meter in air	
Neutron	2.2×10^{3} rem/(hr-g)
Gamma	1.6×10^{2} rad/(hr-g)
Decay heat	
From Alpha decay	18.8 watts/g
From fission	19.7 watts/g
Source volume (excluding void space for helium)	<1 cm^3/g

TABLE 2

ISOTOPIC COMPOSITION OF ^{252}Cf NEUTRON SOURCES

Isotope	Composition Range, Wt%
^{250}Cf	11 to 23
^{251}Cf	3 to 7
^{252}Cf	70 to 86

TABLE 3

IMPURITIES IN CALIFORNIUM PRODUCT

Impurity	Maximum Content
^{244}Cm	~1000 ppm
Total actinides and lanthanides	Equal to Cf content
Nonradioactive cations	Four times Cf content[a]

[a] Except as much as one milligram of lanthanide carrier may be present in small amounts of californium (500 micrograms or less).

TABLE 4

ESTIMATED QUANTITIES AND PRICES OF ^{252}Cf

	Early 1970's	Mid 1970's	Late 1970's	Early 1980's
Quantities Available (Avg), g/yr	0.75-1.0	5-10	20-50	40-250
Estimated Unit Price, $/μg	15-25	5-7	2-3	0.5-1.5

TABLE 5

SHIELDS FOR SMALL CALIFORNIUM SOURCES

Size, gal [a]	Drum Diameter, in.[a]	Shipping Limit, μg ^{252}Cf[b]	Weight, lb [a]
15	15-1/2	17	150
30	18	62	250
55	22-1/2	93	450
70	27	180	600
100	30	240	900
130	33	313	1200
170	36	400	1500
230	40	525	2000
300	44	700	2600

[a] Monsanto Research Corporation, Radioactive Sources Handbook and Products Catalog (March 1968).

[b] Source inventories were calculated with the ANISN code.

TABLE 6

ACTIVATION ANALYSIS OF MINERALS

Sensitivities for Measurement of Elements in Representative Minerals by a Rapid ^{252}Cf Irradiation and Direct Counting

Element	Mineral	Radionuclide Daughters	Half-Life	Detectable Concentrations[a] 1-10, ppm	10-100, ppm	0.01-0.1, %	0.1-1, %	1-10, %
Aluminum	All Minerals	^{28}Al	2.30 min				X	
Antimony	Stibnite	^{122}Sb	2.8 days					
		^{122m}Sb	4.2 min					X
		^{124m}Sb	21 sec					
Arsenic	Arsenopyrite	^{76}As	26.5 hr				X	
Barium	Witherite	^{133m}Ba	38.9 hr					
		^{139}Ba	83 min				X	
Cobalt	Cobaltite	^{60m}Co	10.5 min				X	
Copper	Chalcopyrite	^{64}Cu	12.8 hr				X	
		^{66}Cu	5.1 min					
Dysprosium	Gadolinite	^{165}Dy	2.35 hr		X			
		^{165m}Dy	1.26 min					
Fluorine	Gadolinite	^{20}F	11 sec			X		
Gold	Quartz	^{198}Au	64.8 hr		X			
Indium	Chalcopyrite	^{116m}In	54 min	X				
Magnesium	Magnesite	^{27}Mg	9.5 min				X	
Manganese	All minerals	^{56}Mn	2.58 hr			X		
Mercury	Cinnabar	^{205}Hg	5.2 min					X
Niobium	Columbite	^{94m}Nb	6.3 min					X
Molybdenum	Molybdenite	^{101}Mo	14.6 min			X		
Scandium	Scheelite	^{46m}Sc	20 sec	X				
Selenium	Chalcopyrite	^{77m}Se	18 sec	X				
Silver	Argentite	^{108}Ag	2.4 min		X			
		^{110}Ag	24 sec					
Strontium	Witherite	^{87m}Sr	2.8 hr				X	
Titanium	Rutile	^{51}Ti	5.80 min				X	
Tungsten	Scheelite	^{183m}W	5.3 sec				X	
		^{187}W	24 hr					
Vanadium	Any mineral	^{52}V	3.77 min		X			

[a] ^{252}Cf source of 1 milligram
Sample weight of 5 kilogram
Irradiation time of 2 minutes
Counting time of 2 minutes
Ge(Li) diode size of 80 cm^3 and resolution of 3 kev
Expected precision at the stated detectable concentrations is ±3 to 15%

TABLE 7

PREFERRED REACTIONS AND OBSERVED YIELDS FOR 24 ELEMENTS ACTIVATED BY CALIFORNIUM-252

Element	Compound	Reaction	Energy,[a] Mev	Half-Life	Cross Section[a]	Yield[d]
V	V_2O_3 in $CaCO_3$	$^{51}V(n,\gamma)^{52}V$	1.43	3.75 min	4.5 b (Th)	1.8×10^6
Mn	MnO_2 in $CaCO_3$	$^{55}Mn(n,\gamma)^{56}Mn$	0.85 (1.81,2.13)	2.85 hr	13.3 b (Th)	6.3×10^5
Al	Al_2O_3 in $CaCO_3$	$^{27}Al(n,\gamma)^{28}Al$ $^{27}Al(n,p)^{27}Mg$	1.78 0.84 (1.01)	2.3 min 9.5 min	0.21 b (Th) 2.8 mb (F)[b]	1.8×10^5 3.0×10^4
Au	Au Powder in Ore Mix[c]	$^{197}Au(n,\gamma)^{198}Au$ $^{197}Au(n,n')^{197m}Au$	0.41 0.29	2.7 days 7.2 sec	9.9 b (Th) 0.3 b (F)[b]	1.2×10^5 2.4×10^4
Ag	Ag_2O in $CaCO_3$	$^{109}Ag(n,\gamma)^{110}Ag$	0.66	24.5 sec	113 b (Th)	1.2×10^5
Ba	$BaCO_3$	$^{137}Ba(n,n')^{137m}Ba$	0.66	2.6 min	0.26(F)[b]	5.4×10^4
Cu	CuO	$^{65}Cu(n,\gamma)^{66}Cu$	1.04	5.1 min	2.3 b (Th)	5.0×10^4
Si	SiO_2	$^{28}Si(n,p)^{28}Al$	1.78	2.3 min	4 mb (F)[b]	2.0×10^4
Ti	TiO_2	$^{50}Ti(n,\gamma)^{51}Ti$	0.32 (0.93)	5.8 min	0.14 b (Th)	1.4×10^4
Sn	Sn Powder in $CaCO_3$	$^{124}Sn(n,\gamma)^{125m}Sn$	0.33	9.5 min	0.2 b (Th)	1.3×10^4
Cr	Cr_2O_3	$^{52}Cr(n,p)^{52}V$	1.43	3.75 min	See text	7.6×10^3
P	Na_2HPO_4	$^{31}P(n,\alpha)^{28}Al$	1.78	2.3 min	1.4 mb (F)[b]	5.6×10^3
Mg	MgO	$^{26}Mg(n,\gamma)^{27}Mg$	0.84 (1.01)	9.5 min	27 mb (Th)	5.2×10^3
Co	CoO	$^{59}Co(n,\gamma)^{60m}Co$	1.33	10.5 min	16 b (Th)	3.9×10^3
Mo	MoO_3	$^{100}Mo(n,\gamma)^{101}Mo$ $^{101}Mo \xrightarrow{\beta} {}^{101m}Tc$	0.19 0.31	14.6 min 14 min	0.2 b (Th)	3.8×10^3 3.3×10^3
Na	Na_2HPO_4 Na_2CO_3 NaCl	$^{23}Na(n,\gamma)^{24}Na$	1.38	15 hr	0.54 b (Th)	3.1×10^3 2.7×10^3 0.8×10^3
Cl	PVC	$^{36}Cl(n,\gamma)^{37}Cl$	2.17 1.60	37.2 min	0.4 b (Th)	2.0×10^3 1.9×10^3
	NaCl		2.17 1.60			9.3×10^2 7.5×10^2
Fe	Fe_2O_3	$^{56}Fe(n,p)^{56}Mn$	0.85 (1.81,2.13)	2.58 hr	0.9 mb (F)[b]	7.7×10^2
K	K_2CO_3	$^{41}K(n,\gamma)^{42}K$	1.52	12.4 hr	1.1 b (Th)	6.1×10^2
Ca	$CaCO_3$	$^{48}Ca(n,\gamma)^{49}Ca$	3.09 (4.1)	8.8 min	1.1 b (Th)	6×10^4
Zn	ZnO	$^{65}Zn(n,p)^{66}Cu$	1.04	5.1 min	See text	1.6×10^2
Ni	NiO	$^{64}Ni(n,\gamma)^{65}Ni$	1.48 1.12	2.56 hr	1.5 b (Th)	6.8×10 5.5×10
Pb	PbO	$^{204}Pb(n,n')^{204m}Pb$	0.90	67 min	15 mb (F)	1.7×10
S	S	None detected				0

[a] Thermal neutron activation cross section, γ-ray and isotope abundances, and other relevant data taken from C. M. Lederer, J. M. Hollander, and I. Perlman. *Tables of Isotopes*. 6th ed., John Wiley and Sons, Inc., New York (1967).

[b] Fission neutron activation cross sections taken from:
R. S. Rochlin. *Nucleonics 17*(1), 54 (1959).
C. E. Mellish. *Nucleonics 19*(3), 114 (1961).
H. H. Kramer and W. H. Wahl. *Nucl. Sci. Eng. 22*, 373 (1905).
W. Kohler and K. Knopf. *Nukleonik 10*(4), 181 (1967).

[c] Approximately 50% SiO_2, 20% Al_2O_3, 20% $CaCO_3$, and 10% Fe_2O_3.

[d] Counts/g of element per 10^9 n/sec of source output.

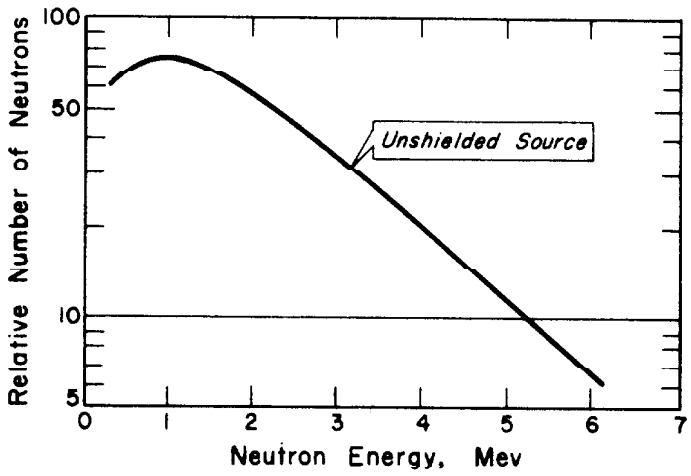


FIG. 1 NEUTRON ENERGY SPECTRUM OF ^{252}Cf

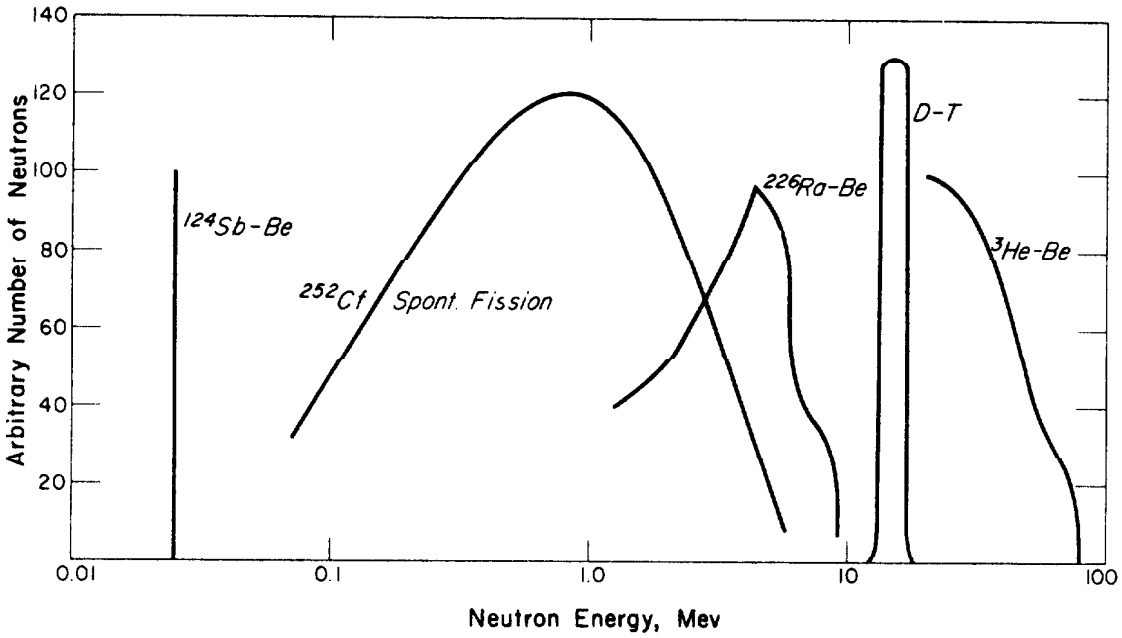


FIG. 2 NEUTRON ENERGY SPECTRA OF VARIOUS NEUTRON SOURCES

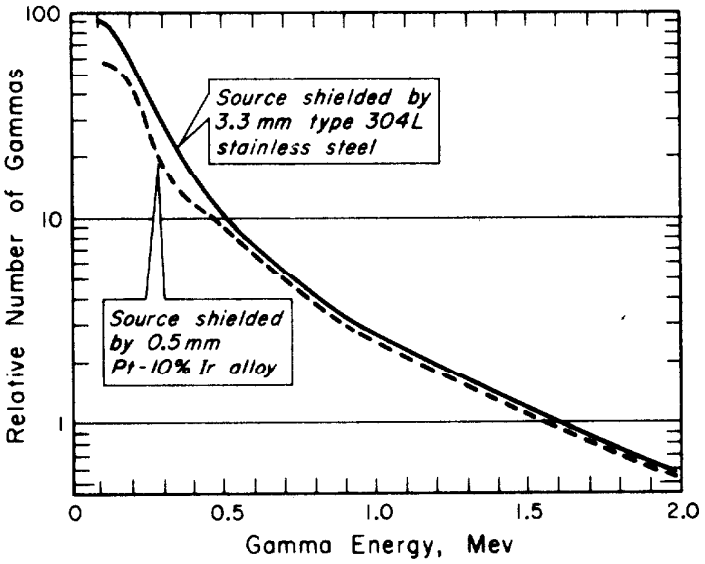


FIG. 3 GAMMA ENERGY SPECTRUM OF ^{252}Cf

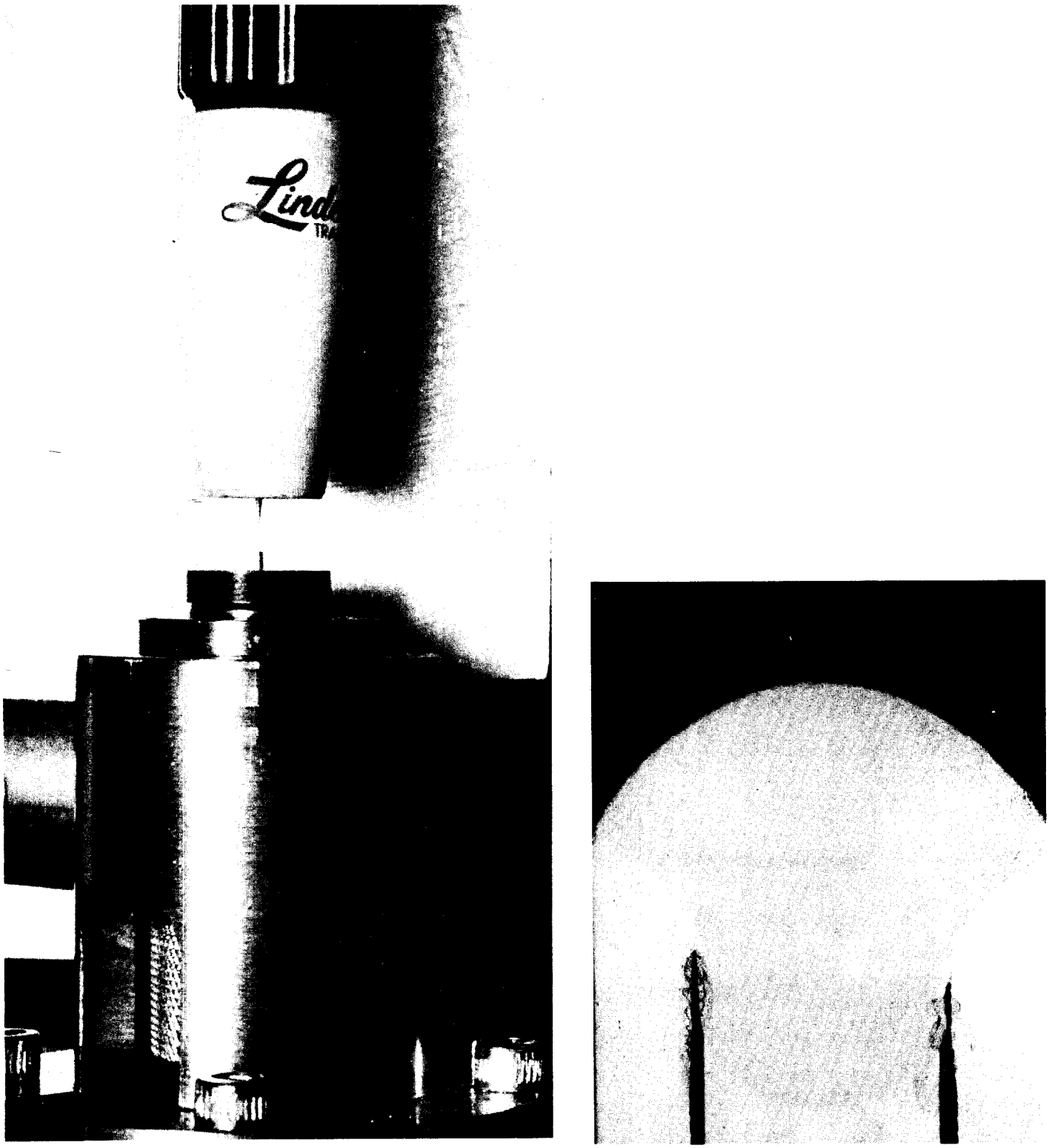


FIG. 4 END WELD OF ^{252}Cf RADIOTHERAPY SOURCE

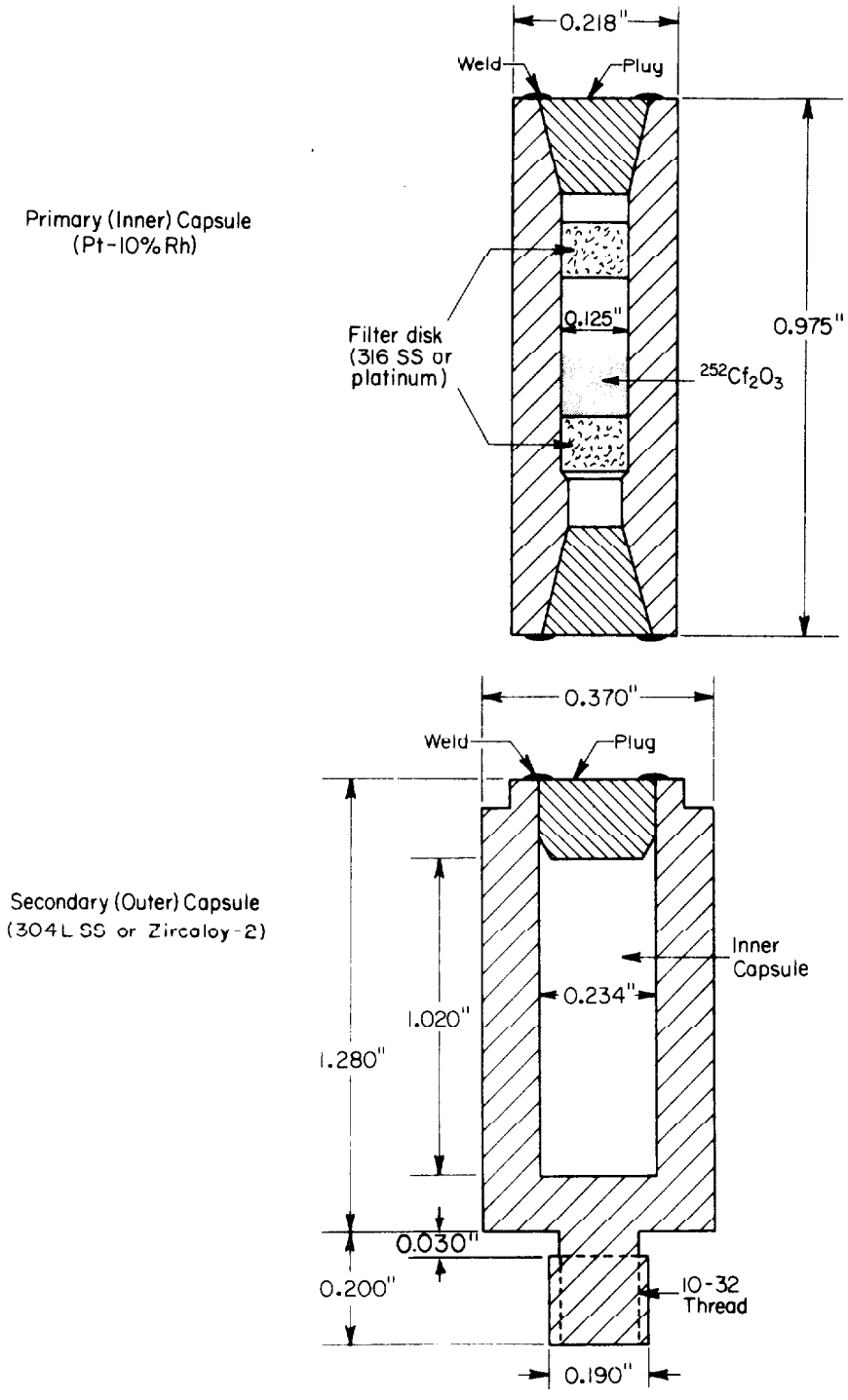


FIG. 5 ENCAPSULATION BY PRECIPITATION AND FILTRATION

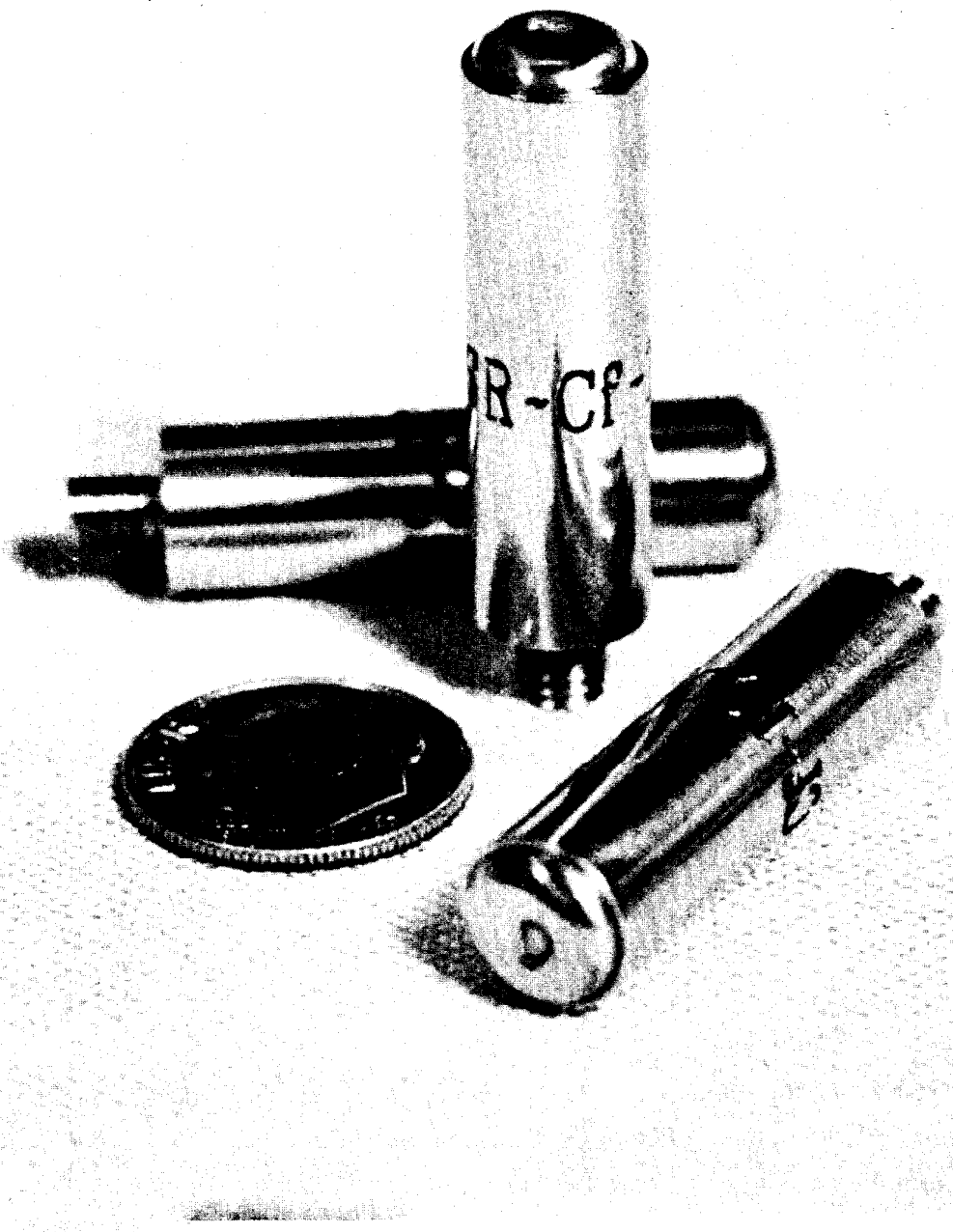


FIG. 6 ^{252}Cf Neutron Sources (SR-Cf-100) SERIES

(Prepared by precipitation and filtration technique for AEC's Market Evaluation Program)

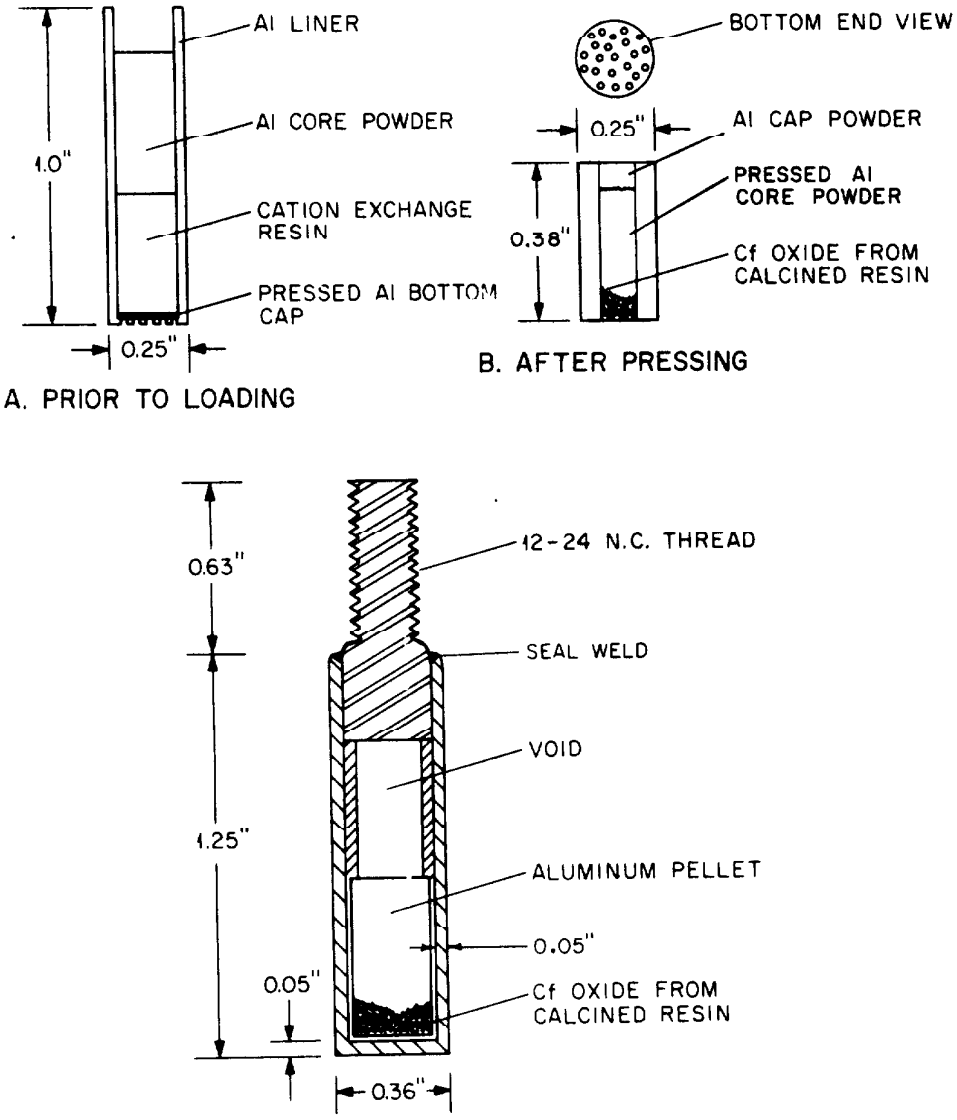


FIG. 7 ^{252}Cf NEUTRON SOURCE — ORNL RESIN LOADING TECHNIQUE

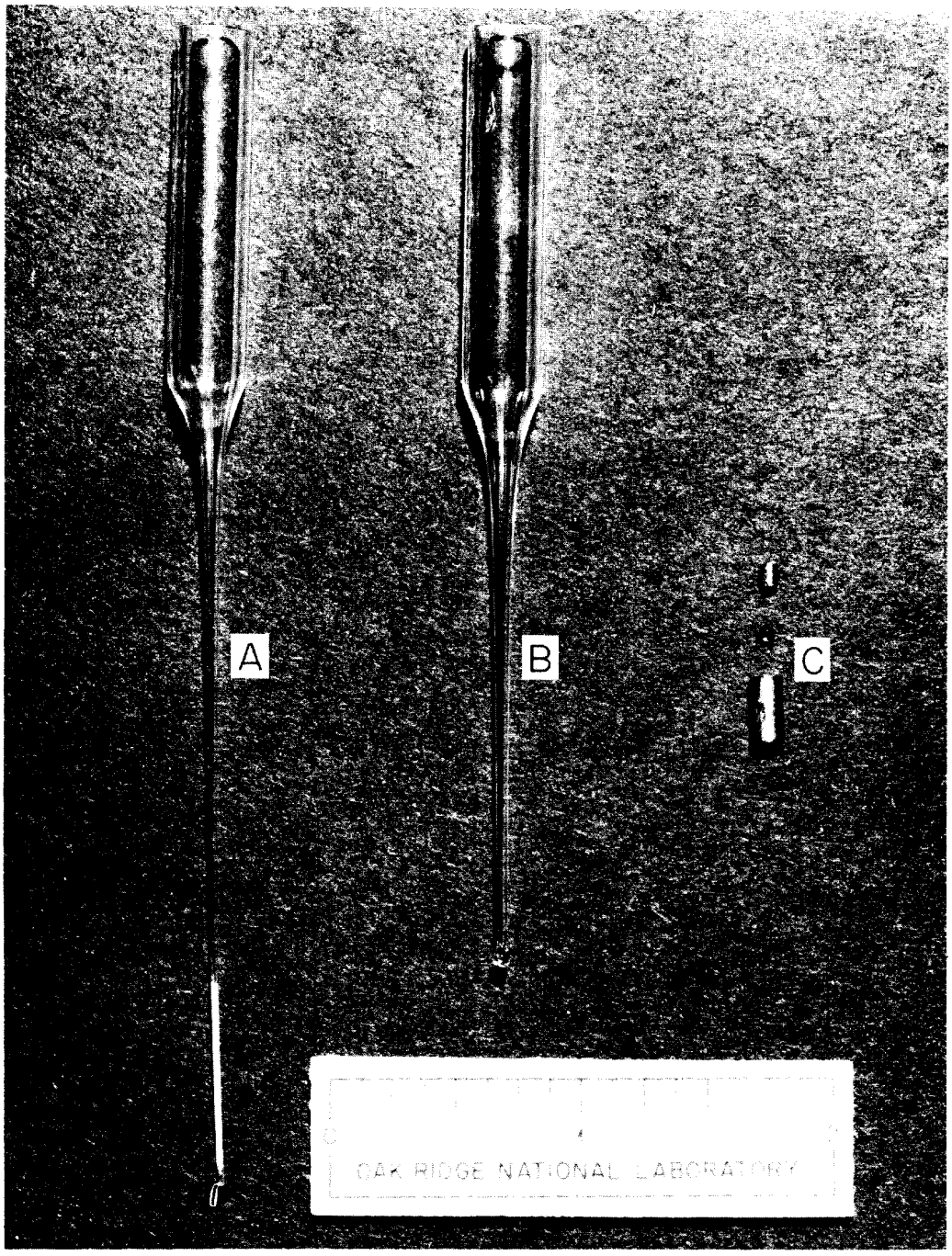
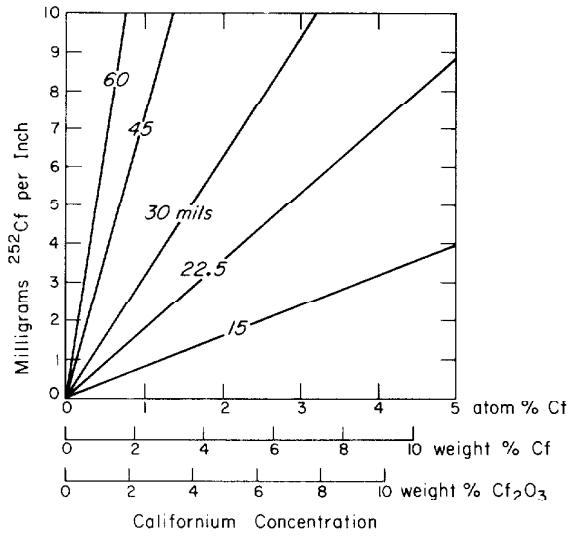
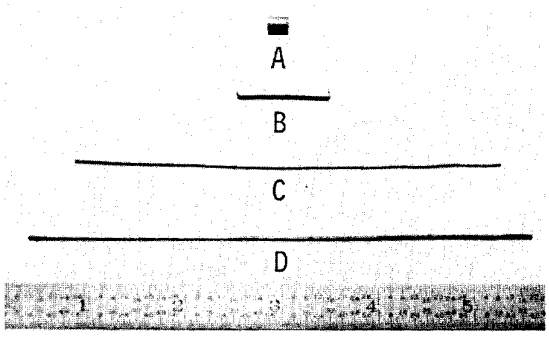


FIG. 8 ^{252}Cf NEUTRON SOURCE — ORNL FUSED QUARTZ TECHNIQUE





Typical Forms of $^{252}Cf_2O_3$ Cermet Made with 1 at. % Sm_2O_3 Dispersed in Palladium. *A* Sintered Pellet (0.180-in. diameter by 0.220 in. long), *B* Rod (rolled, square cross section 0.062 in.), *C* Sheathed Wire (swaged, 0.025-in. OD, 0.017-in. ID core diameter), *D* Wire (rolled, square cross section 0.030-in. diameter).

FIG. 9 ^{252}Cf ALLOY WIRE

FIG. 10 SHIELDED MOBILE TRAILER FOR ^{252}Cf
(Kerr-McGee Corporation)

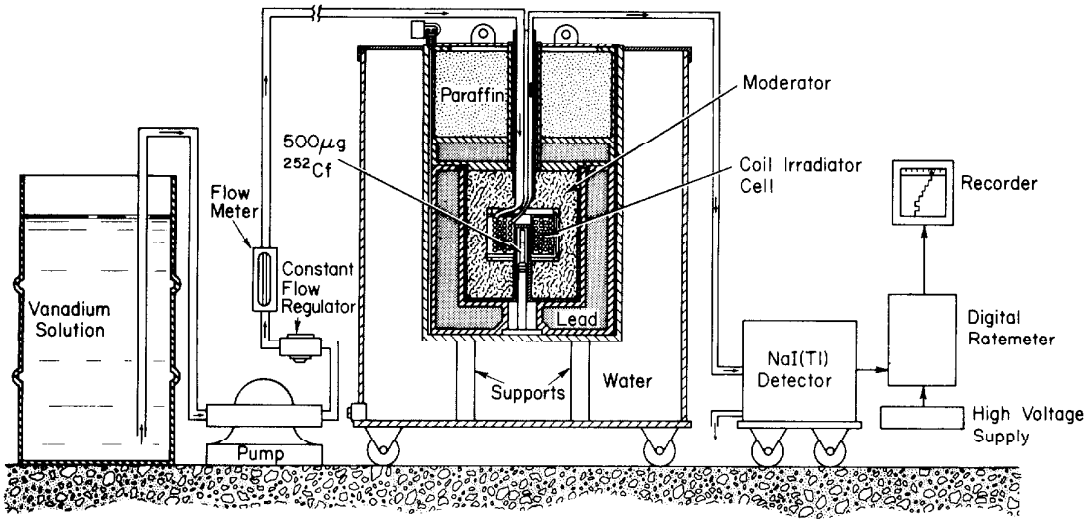


FIG. 11 ON-STREAM VANADIUM ANALYZER

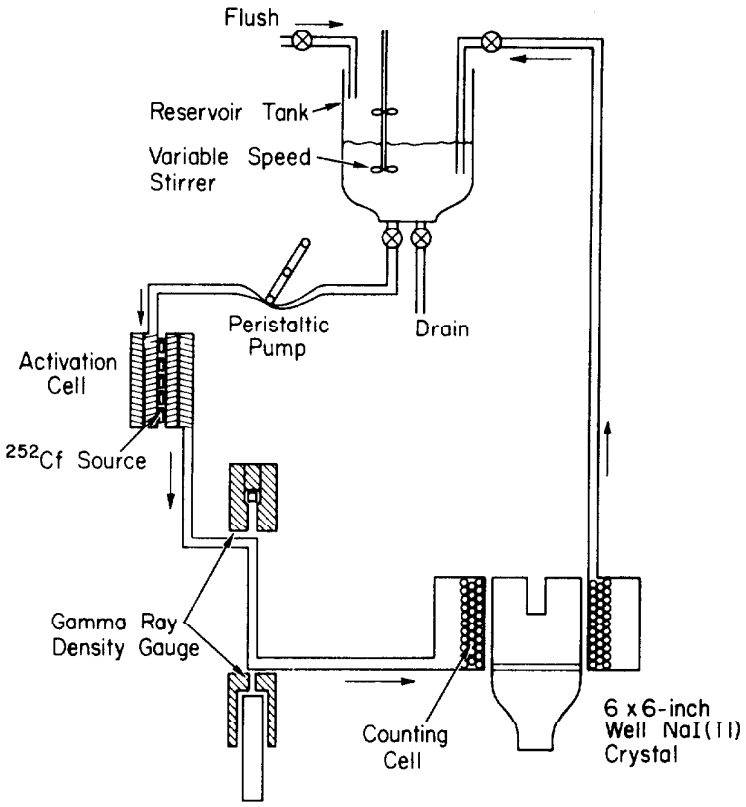
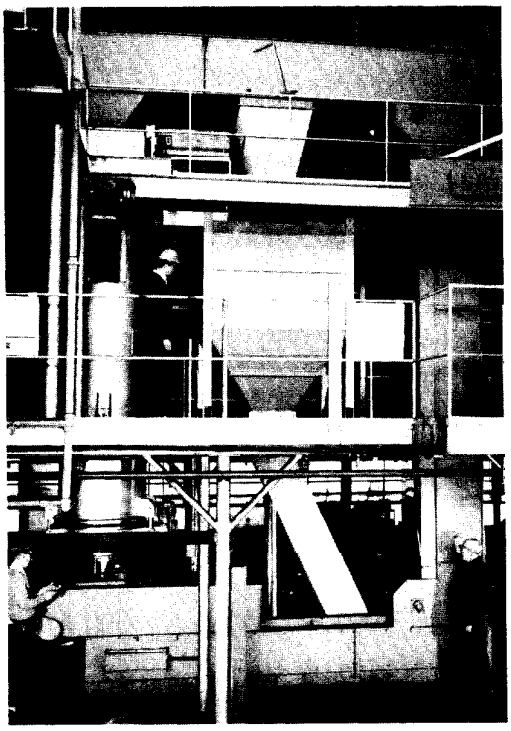


FIG. 12 SLURRY LOOP FOR ON-STREAM ANALYSIS
(Columbia Scientific Industries)



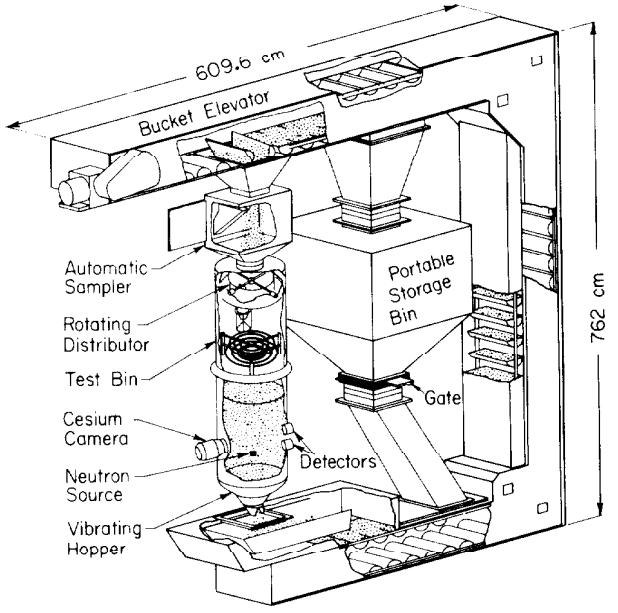


FIG. 13 COAL RECYCLE SYSTEM FOR SULFUR METER

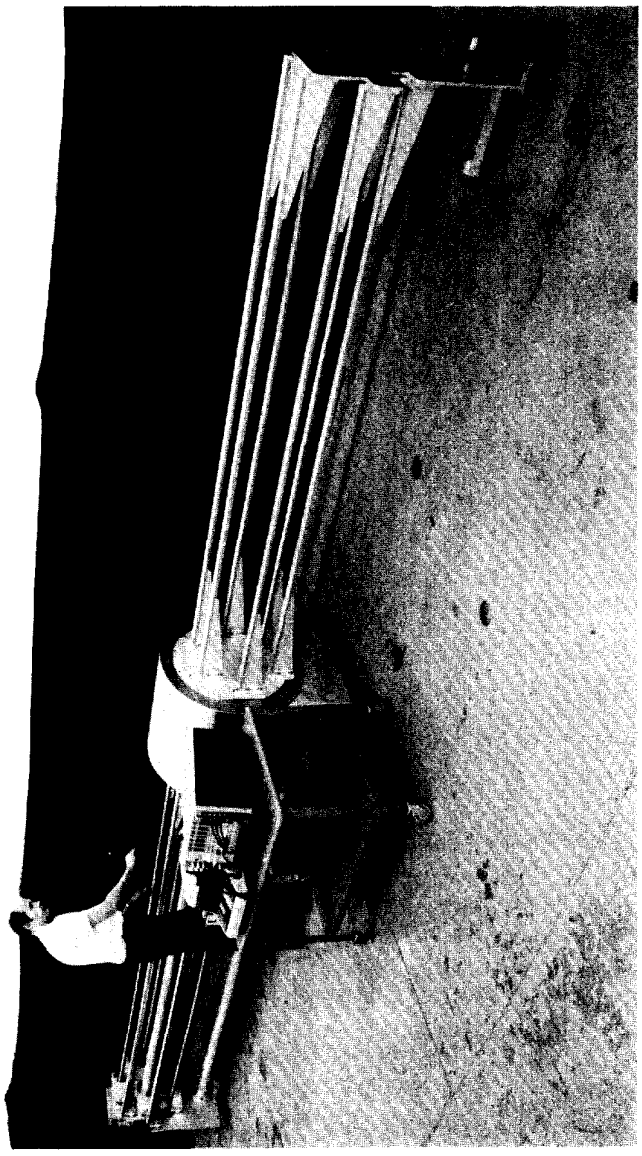
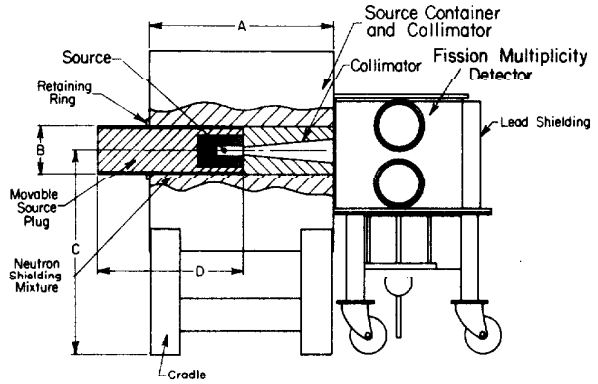


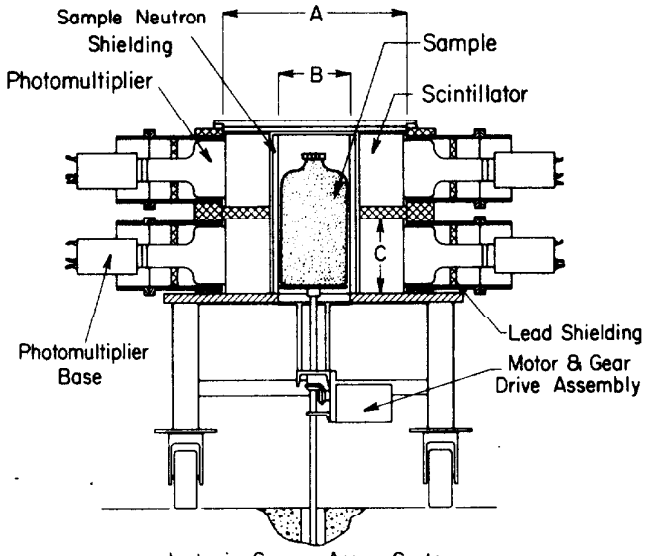
FIG. 14 REACTOR FUEL ROD ASSAY SYSTEM



Isotopic Source Assay System

	No. 1	No. 2
A	24"	24"
B	5-7/8" Dia	6-1/16" Dia
C	23"	26-1/8"
D	19"	19"

Source Container and Collimator



Isotopic Source Assay System

	No. 1	No. 2
A	16" Dia	16-1/4" Dia
B	6" Dia	6-1/4" Dia
C	6-1/2"	6-1/2"

Detailed View of the Fission Multiplicity Detector

FIG. 15 SOURCE CONTAINER AND FISSION MULTIPLICITY DETECTOR (Gulf Energy and Environmental Systems, Inc.)

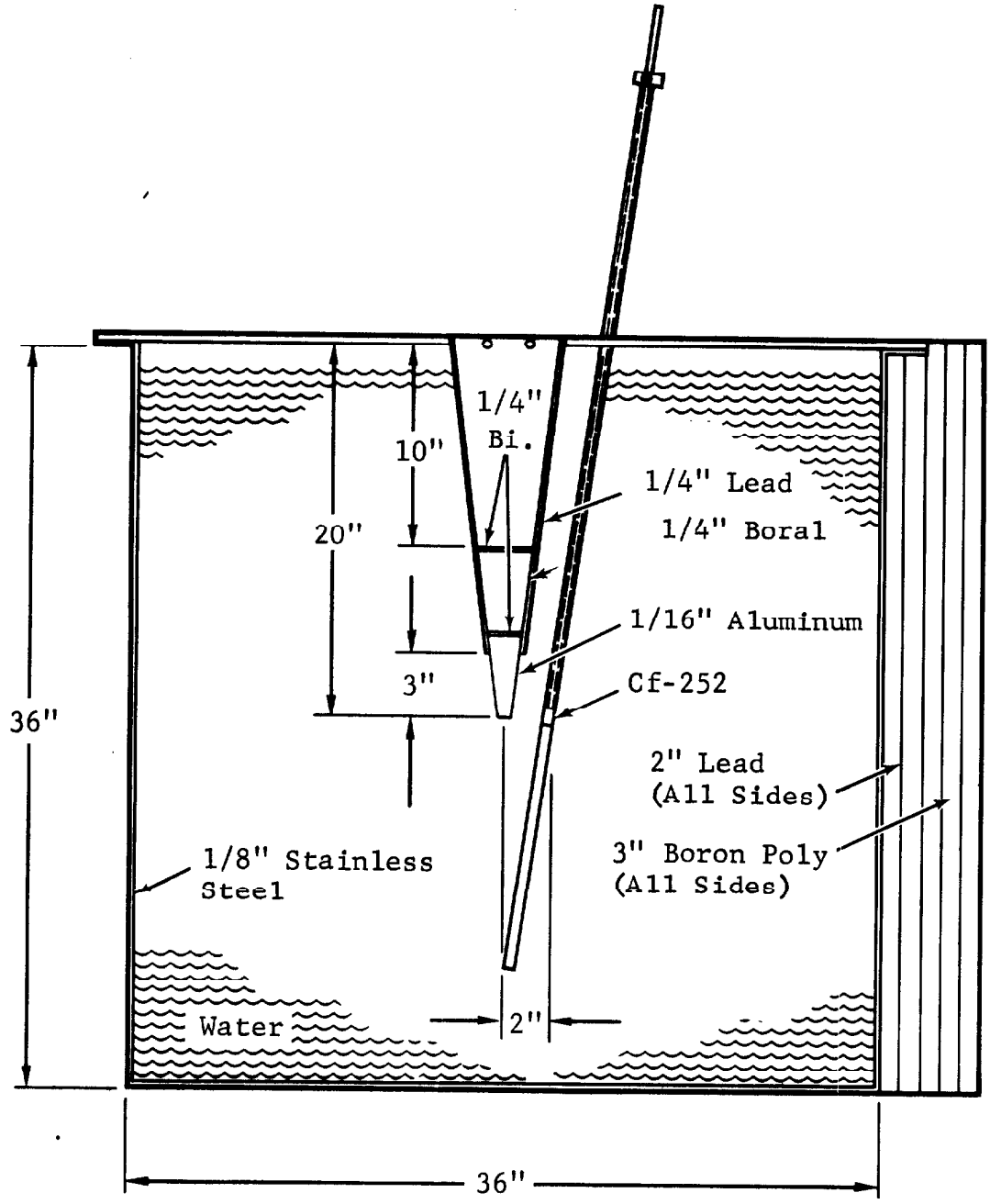


FIG. 16 NEUTRON RADIOGRAPHY FACILITY, ~1 mg of ^{252}Cf
(General Dynamics Convair Aerospace Division)

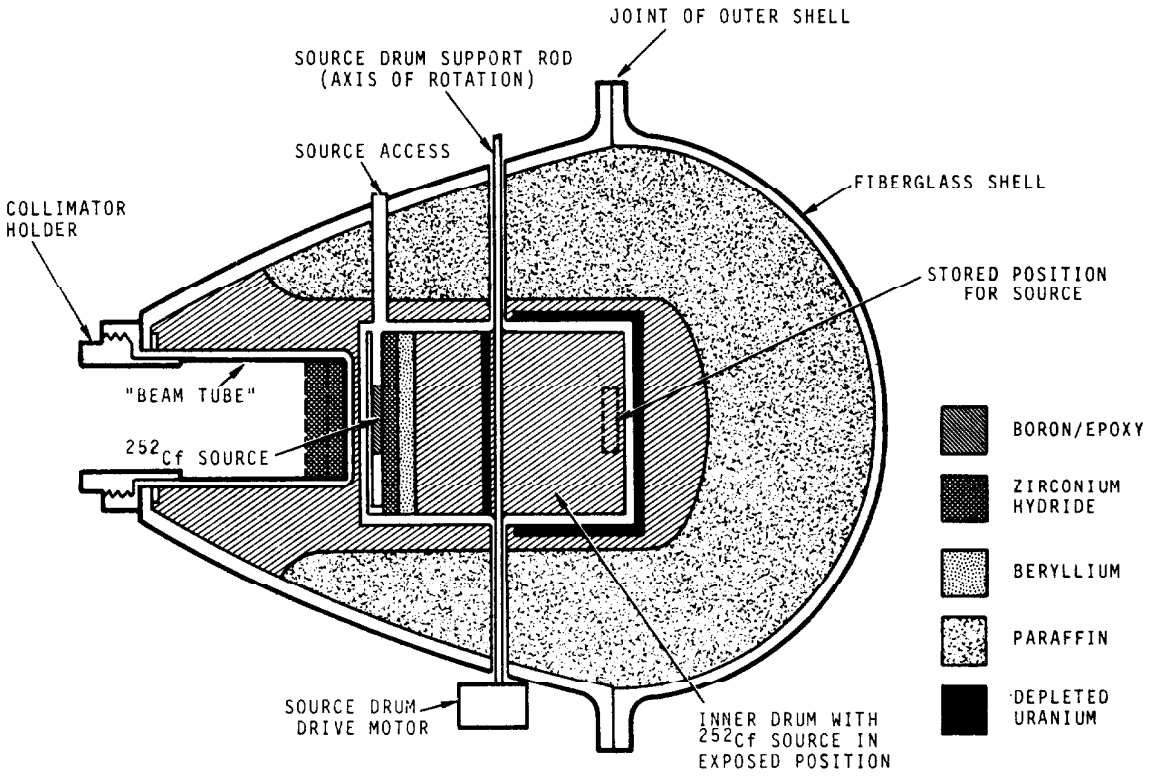


FIG. 17 INTERIOR DETAILS OF ^{252}Cf NEUTRON CAMERA
(Battelle-Northwest)